AUTOMATION LESSONS LEARNED AT NASA/GODDARD SPACE FLIGHT CENTER

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ABSTRACT

The automation of five mission control centers at NASA's Goddard Space Flight Center is examined to document lessons learned for future missions. Automation is examined not from a technology perspective but from an implementation and operational use perspective.

Information is presented from both developers and operators regarding the capabilities and tools used for automation. The capabilities and approaches for each control center is described for each function, including comments on the relative difficulty in providing a capability and the merits of the tools and techniques used. Experiences common to multiple missions are identified, as well as lessons learned and recommendations that can be used by other missions, such as:

- Basic scripted contacts with post-contact notification are safely and easily implemented and provide substantial cost savings.
- Complex automation that includes automated corrective action requires advanced programming skills and is much more expensive to develop and maintain.
- Automation has an overall positive effect on employee job satisfaction, especially by reducing repetitive tasks and reducing shift work.
- There is relatively little perceived need to increase the automation for functions other than spacecraft contacts
- Additional economies may be possible by providing a library of existing automation scripts, utilities, tools, and applications.
- Empowering the operations team to develop and maintain a large portion of the automation greatly increases acceptance, speeds development, and helps maintain skills and mission involvement.

Attention was given to the impact on operations staffing. As higher levels of automation become the norm across most missions, there is a potential for significantly changing the approach to staffing mission operations. The immediate impact is to reduce individual team size. Secondary issues that are addressed include knowledge and skill retention, the sharing of mission roles between operations and other functions, and retaining skilled and motivated people to oversee spacecraft health and mission performance.

1. INTRODUCTION, PURPOSE, AND SCOPE

This study is part of the operations concept development for future missions that potentially would use the new Goddard Mission Services Evolution Center (GMSEC) architecture. The GMSEC architecture enables quick and easy integration of functional components by using middleware to route and filter messages among the application components. This middleware will also facilitate advanced levels of automation by enabling automated process flow, easing the management of the additional status and control messages that are part of automated systems, and enabling the collection and analysis of end-to-end status information. The purpose of the study is to identify lessons learned from the currently automated missions at NASA/GSFC and to derive recommendations for GMSEC. Areas studied include:

- Automation features that have been most beneficial
- The relative costs of different approaches to automation
- The mission circumstances that might affect the selection of features
- Spacecraft and ground system facilitators and inhibitors to automation
- Recommended additional automation features

Automation is the transfer of human activities to systems, usually computers and related systems for taking actions. This can also include transferring human reasoning. Autonomy exists when there is enough encoded reasoning for the system to act alone, within some limits. Autonomy is not an absolute condition, but a matter of degree. Just as a person's expertise and available tool set limit their autonomy, a system is similarly limited, and can be augmented over time with additional "training" or tools.

2. STUDY METHODOLOGY

Five mission teams at NASA/GSFC experienced with automated operations were interviewed: Landsat 7, The Rossi X-ray Timing Explorer (RXTE), Small Explorers (SMEX), Earth Observing-1 (EO-1, a New Millennium technology mission), and Medium Explorer (MIDEX) missions, Microwave Anisotropy Probe (MAP) and Imager for Magnetopause to Auroral Global Exploration (IMAGE). Members of the operations team automated all of the missions, except for RXTE. For RXTE, both the operations leads and the developers were interviewed to get information on operations impact and satisfaction, as well as design and development experience.

A preliminary summary of all interview results was distributed to all interviewees to ensure that their comments were correctly understood. The authors then evaluated the responses with respect to personal knowledge of mission operations, especially issues that occur in managing mission operations teams. After deriving preliminary implications for GMSEC, we sought additional comments from mission operations leads, which were considered in making our final recommendations.

3. SUMMARY OF INTERVIEW RESULTS

The interviews had four broad topic areas:

- The extent of the automation
- Spacecraft and ground system factors contributing to the automation effort
- The automation implementation approach
- Team assessment of their automation

A summary of the responses to the questions is given below.

o The Extent of the Automation

In all cases, the primary reason for automation was to reduce operations costs via a reduction in staff, with some also citing operator error reduction. Thus automation has been concentrated on spacecraft contact operations, where shifts can be eliminated to reduce staffing needs. Table 1 shows which aspects of contact operations have been automated. The core functionality common to all systems is increased scripting of routine pass operations with notification of events that might require operator attention. All use manual intervention for contacts performing special operations, such as maneuvers. Among these missions, only RXTE uses an expert system for monitoring and controlling pass execution; and thus is the only mission to apply inference/logic. (The RXTE expert systems have previously been used for the Compton Gamma Ray Observatory and the Extreme Ultra-Violet Explorer, both of which have ended operations.) None of these missions have automation initiate corrective actions for spacecraft conditions other than the routine execution of contact activities, such as data downlink.

RXTE also has many ways of checking and correcting ground system problems. It checks that the expected messages are being generated, and in the event of three consecutive errors takes a corrective action dependent on the nature of the application. The system also checks for network connections, particularly for paging, which requires a connection outside the closed network. Because several Mission Operations Centers (MOCs) share a closed network environment, the automation can switch to another MOC's router to get outside the closed network. SMEX checks that the real-time application is functioning properly before a pass and will reboot the system when necessary.

Table 1. Summary of automation added to spacecraft contact operations for five missions

	Landsat	RXTE	SMEX	EO-1	MAP/ IMAGE
Process inputs	Y	Y	Y		Y
System configuration	Y	Y	Y		Y
Process flow	Y	Y	Y	Y	Y
Process/event/status monitoring	Y	Y	Y	Y	Y
Alert notification	Y	Y	Y	Y	Y
Process recording and reporting	Y	Y	Y	Y	Y
Ground system corrective actions		Y	Y		
Inference/Logic		Y			
Routine S/C commanding/uploading		Y		Y	
S/C corrective actions					

No automation has been added to existing mission planning tools, which are generally fairly automated already. No automation has been applied to spacecraft analysis, though EO-1, RXTE, SMEX, and MIDEX provide automatic processing of engineering data for analysis. Spacecraft analysis continues to be done primarily by manually examining plots of critical telemetry points.

o Spacecraft and Ground System Factors

Spacecraft characteristics that generally add complexity to fully automating operations include: spacecraft control for tape recorder management, manual overrides, data dropouts, loads, and contingency responses. Mission specific responses follow:

- RXTE: Antenna failure resulted in limited Tracking and Data Relay Satellite System viewing: contacts must be timed around science driven attitude and real-time science slews require automation be overridden. Automation must distinguish different pass types.

- SMEX: Non-programmable watchdog timers force the team to schedule new passes when one is missed.
- MIDEX: IMAGE can only address data by byte address, making it complicated to identify dump locations for filling in data gaps. Load formats require memory addresses to be specified, and if there are any errors in the load format, the spacecraft will go into a safe-mode, which significantly interrupts operations. The onboard recorder is easily corrupted, requiring a stop/restart in pass plans as a preventive measure.
- EO-1: The spacecraft's small recorder size and the mission's aggressive science schedule leave no room for obtaining ground station contingency coverage when a ground station anomaly causes failure to capture science data .

Spacecraft characteristics that generally make operations and automation easier include: data recorder margin to allow for pass redundancy, time-tagged commanding, self-safing, and redundant failover for those with redundant components. Mission specific responses follow:

- Landsat: There is only one spacecraft state to check on. The spacecraft has autonomous attitude control mode changes and power monitoring.
- RXTE: The spacecraft can execute slews with only the slew vector defined. (Before the antenna failure, RXTE could slew without redoing the science schedule.) The spacecraft records events and autonomously dumps data.
- MIDEX: MAP on-board data structure facilitates retransmission. IMAGE has no attitude control or concern about solar array orientation.

The following ground system challenges were mentioned. The Deep Space Network (DSN) requires verbal instruction/ authorization for any changes to passes. Poorly structured pass scripts (procs) that have to be integrated add complexity. Lack of interface to the operating system for linking control among applications makes automation more difficult, as does managing the transfer of command privileges back to automation after a manual override.

Some ground system features make automation easier. Software-based processes are easier to automate than hardware (e.g., front ends, power control). Mission specific responses follow:

- Landsat: Their Telemetry and Command (T&C) system is sufficiently reliable that there is no need for hot back-ups.
- RXTE: Because their MOC has a network of redundant workstations with flexible communications, automation can run from anywhere in the MOC.
- SMEX: Their T&C system's configuration monitors can generate monitoring events. Continuously running STOL procedures can set up passes from a schedule. (STOL -Spacecraft Test and Operations Language- is a scripting language used for spacecraft control at GSFC. It varies slightly from mission to mission, with newer versions having greater capabilities.)
- MIDEX: Their T&C system's STOL can run parallel scripts and provides directives that can call functionality through the operating system. It can also run passes with a plan input as a text file and generates pseudo-telemetry to aid monitoring. Internal relational database is much easier to use than Oracle. Mission differences are in a database so that tools can be easily transferred between missions.

o **Automation Implementation**

Table 2 lists the various software packages and languages are used for automating each MOC. TPOCC (Transportable Payload Operations Control Center), ITOS (Integrated Test and Operations System), and ASIST (Advance Spacecraft Integration and System Test) are T&C systems developed at GSFC. TPOCC, the first workstation based system, was used on most missions until several years ago. ITOS and ASIST were developed for spacecraft integration and test, and have become the GSFC systems for operations in recent years. Genie and GenSAA are Clips-based expert systems developed at GSFC; GenSAA primarily provides monitoring and analysis rules while Genie is used to build and execute processes. SERS monitors events and manages subsequent notifications. It was originally developed at GSFC and commercialized by Mobile Foundations, Inc. Mark/Space sells Page Now.

When asked why they chose the packages they did, those that built their own capabilities were avoiding software licensing and maintenance cost, when they could get by with a simpler system that they could easily modify themselves.

Table 2. Software packages and languages used for automation for five missions

	Landsat	RXTE	SMEX	EO-1	MAP/ IMAGE
Scripting	STOL, some Perl for file transfer, Hypercard	Perl, Unix scripts/Chron jobs, Genie	Perl, STOL, Unix scripts/Chron jobs	Perl, STOL	Perl, STOL
Event monitoring	TPOCC	TPOCC	ITOS	ASIST	ASIST
Notification	Page Now	Team built	SERS	Team built	SERS
Scheduler	STOL	Genie	STOL	Unix AT jobs	STOL

- Landsat: They tried Altair but it did not work well with TPOCC and there was no need for logic to help analyze spacecraft problems. New releases required a lot of rework. (Altair is ground system that uses state modeling for monitoring the spacecraft.)
- RXTE: Clips (the expert system language in GenSAA) for scripting was rejected: Perl was easier and required less code.
- SMEX: They decided not to use Genie/GenSAA, as there was no need for real-time reaction.
- MIDEX: Altair took too much time to apply for their needs.
- EO-1: For what they needed, they could build their own paging system cheaper than using SERS

No one reported having serious technical problems when developing automation. Table 3 shows the effort to develop and maintain each mission's automation, and other related information.

Table 3. Automation level of effort and related information

	Landsat	RXTE	SMEX	EO-1	MAP/ IMAGE
Staff months to develop	9	48	Part of FOT activities	Part of FOT activities	IMAGE – 4 MAP - 12
Automation shell vs. re-engineering	Shell only	Shell plus some proc changes	Primarily scripts	Shell plus some proc changes	IMAGE – shell. MAP- shell + proc rework
Reuse from previous mission	None	Very little.	None	None	MAP reused IMAGE
Hours/year to maintain	40	400	Negligible	Negligible	Negligible

The following is each team's assessment of how easily their automation could be adapted to a different mission:

- Landsat: Scripts are mission unique
- RXTE: Health and safety monitor has been made user configurable for new missions, though Genie/GenSAA is designed around specific T&C systems. For new missions a 2 person team with necessary system skills can automate a typical new mission in about 11 months: 2 for knowledge capture and setting up accounts, 3 to build a baseline system, and 6 for testing and tuning.
- MIDEX and EO-1: automation would be very easy to adapt to other missions using the ASIST T&C system.

o **Team assessment of their automation**

All thought their automation was reliable and easy to use, and liked the ability to get information at home when they were paged. Those that built their own automation liked that it was inexpensive and they could easily maintain and adapt it to mission changes themselves. Some teams mentioned specific features and benefits:

- Landsat: Automation added flexibility to their work schedule by extending periods of automated operations.
- RXTE: Autonomous command uplink and verification is necessary for RXTE lights-out operations. Their automation includes a control panel to easily start and stop automation.
- SMEX: SERS monitors more parameters on SMEX than the Flight Operations Team (FOT) did.

The impact of automation on training requirements was generally small. Most teams schedule some proficiency training on manual operations. SMEX identified a need for a good flow chart of the automated operations process and commented that deep cross-training and multi-tasking of people made them harder to replace. MIDEX has an additional training module on the automation.

Automation has had an overall positive effect on job satisfaction. Most of the automation on these missions reduces tedious tasks and frees up people for more creative tasks, such as process improvement. Elimination of non-prime shifts is preferred by most people and encourages greater team cohesion.

RXTE commented that automation works so well that some people get complacent. Loss of expertise is a concern, and small teams have little capacity for manual operations during anomaly resolution, particularly for missions with many contacts, like RXTE.

Future plans for automation enhancements are summarized below:

- Landsat: They plan to increase the parameters that are monitored by the automation and to provide more descriptive text in notification messages. They have no plans to automate load uplinks.
- RXTE: They would like to add autonomous reboot of front end processors through the network, monitoring the ground system, failover control, a back-up paging system, science data processing monitoring, and make automation more user configurable by consolidating operational parameters into a database for import into the expert system.
- SMEX: They might automate load generation.
- MIDEX: Since these interviews they have replaced SERS to reduce costs. They plan to add live system monitor and more Web capabilities. Event processing is designed to easily add actions other than paging, but this is not planned. They would be reluctant to have automated directives to the DSN, even if they could,

because they do not want DSN operators to get false alarms.

- EO-1: They plan to add automated command load uplink, ground system process monitoring, and conditional state checking.

The missions' teams identified what they would do differently for automating another mission.

- Landsat: Nothing.
- RXTE: Automation should be built into the operations concept from the beginning, so that procs are written to work with the automation in a less complex system. Automation should be user modifiable without going into code (a feature added for the Advanced Composition Explorer mission), or in a language that the FOT can modify, so that the team can respond quickly to spacecraft changes. They recommend keeping automation simple, as complicated systems take a long time to modify.
- SMEX: They would do all scripting in Perl, rather than many different languages they currently use, to ease maintenance. Network capacity and security requirements at GSFC keep changing: they recommend working closely with security to add capabilities that are needed.
- MIDEX: Their configuration monitor has become overly complicated: It would be better if it were all in Perl. They do not really use real-time Web displays, as their missions are so simple that there is not much to watch. They like the idea of replacing pagers with Palms, so they could have multiple screens and check more data remotely. They would take paging off Windows NT for better security and add pseudo state modeling.
- EO-1: Nothing.

4. SUMMARY OF LESSONS LEARNED

Lessons are derived for three areas: Operational needs and processes, development tools and processes, and human factors.

- **Operational needs and processes:**
  1. Automation has been implemented primarily to reduce costs by eliminating staffing for passes, though it also can help reduce risks by eliminating human error.
  2. Most missions have enough self-safing capabilities that spacecraft health and safety does not have to be responded to in real-time. For such missions there is no need for automation to provide real-time spacecraft responses. The primary response that is desired is to assure the successful completion of the pass, especially in retrieving uncorrupted science data, and when needed, completing load uplinks.
  3. Most missions can automate passes using scripting, notification, and the monitoring capabilities built into their real-time system. This automation is easy to build and maintain.
  4. Missions that have a lower tolerance to unsuccessful passes, for example when there are many passes between staffed periods and/or loads to be uplinked on unstaffed passes, will probably require automated corrective actions during the pass. Applying expert systems to handle decisions for many alternative circumstances can increase complexity, increasing development to a few staff years and annual maintenance to more than two staff months. Much of this added effort comes from the need for programming skills beyond that typical of an FOT and the associated knowledge transfer and testing to assure that externally developed automation meets the mission's and team's needs.
  5. There has been little perceived need for adding automation to off-line processes, beyond that already existing within the applications. These functions can be done within the prime shift for most missions, so that adding automation does not provide significant staff savings compared to pass operations. Newer trending systems have been installed, with improved internal automation. However, the primary automation added has been to link planning and spacecraft engineering data processing with the pass execution, so that files do not have to be transferred manually.
- **Development tools and processes:**
  1. The following ground component characteristics ease automation:
     - Convenient message transfer mechanism (e.g., via the operating system on MIDEX) which make them much easier to integrate into automated processes.
     - Data base driven modification for mission customization and updating
  2. Use a common scripting language throughout; Perl was easy to use and recommended.
  3. To the extent possible, have the FOT build and maintain the automation scripts, as modifications to support changes to the spacecraft or mission can be done quickly and cheaply.
  4. There are potential savings from reuse across missions of basic monitor and notification capabilities. The sharing of automation solutions among teams can reduce redundant development effort, but reuse of existing solutions should encourages rather than enforced. The teams ownership of their automation was an important contribution to its success. The primary barrier to sharing seems to be lack of communication among

different teams. A collaborative environment needs to be created that works across teams.

- **Human Factors**

Automation has a favorable effect on the operations environment, particularly if the operations team has developed it themselves. The main issue of automated operations is retaining operations personnel skills and awareness to detect problems, and respond to them when automation cannot. If people are not highly self-motivated, automation can allow them to become complacent and lose operational awareness of the spacecraft. Job scope needs to include ownership of the operations process for assuring mission success to attract motivated people and keep them engaged.

A creative work environment needs to be maintained. An environment that encourages an operations team to maintain the ability to respond to unexpected events also helps retain highly knowledgeable team members. Flight operations teams should continue to have wide latitude to adapt operations processes to specific missions and to continuously improve those processes, including those that are automated. The creative environment also fosters a 'can do' attitude. The maintenance and operations structure of automation should support the teams' problem solving responsibilities and abilities. Otherwise the 'can do' attitude and abilities will be lost.

Our most skilled people tend to value an independent work environment. They prefer to develop solutions themselves, rather than depend on others. The creative energy has usually been concentrated within a few team members who provide technical leadership for the entire team. Loss of one or more of these individuals can have a detrimental effect. Therefore, knowledge capture and management should be integrated into the operation automation development and maintenance processes.

5. RECOMMENDATIONS FOR FUTURE MISSIONS

The automation of routine pass execution with notification of non-nominal conditions, used for most of these missions, can be assumed to be a baseline for future GSFC missions. This level requires little mission unique adaptation beyond that included in the project database referenced by the T&C system and does not add to mission risk. In addition, GMSEC middleware will provide automated workflow between the real-time components and the planning/scheduling and spacecraft data processing systems.

Therefore, a basic automation including these elements should be developed and tested pre-launch as part of the mission ground system adaptation and integration. Reusability of this common level of automation should be considered along with that of any GMSEC component. This would include requirements on automation functions, such as scripting and notification, and requirements on components for messaging (e.g., command and status) interfaces that are necessary for working in an automated environment. Existing automation components should be easily accessible from a component library for adaptation to a new mission.

Having the FOT being responsible for at least basic levels of automation should be part of the GMSEC process for mission implementation. This is supported by current trends in process management, where the tools are configurable by the process owners without significant programming knowledge. Responsibility for changes to the automated operations should be integrated with maintaining skills for manual overrides of automation when necessary and related training and proficiency testing.

ACRONYM LIST

ASIST	Advanced Spacecraft Integration and System Test
DSN	Deep Space Network
EO-1	Earth Orbiter –1
FOT	Flight Operations Team
GenSAA	Generic Spacecraft Analyst Assistant
GMSEC	Goddard Mission Services Evolution Center
GSFC	Goddard Space Flight Center
IMAGE	Imager for Magnetopause to Auroral Global Exploration
ITOS	Integrated Test and Operations System
MAP	Microwave Anisotropy Probe
MIDEX	Medium Explorer
MOC	Mission Operations Center
RXTE	Rossi X-ray Telescope Explorer
SERS	Satellite Emergency Response System
SMEX	Small Explorer
STOL	Spacecraft Test and Operations Language
T&C	Telemetry and Command
TPOCC	Transportable Payload Operations Control Center